

THE EFFECT OF THE ACHILLES TENDON MOMENT ARM ON KNEE JOINT CONTACT FORCE

by

Ashley E. Warren

A Senior Honors Project Presented to the

Honors College

East Carolina University

In Partial Fulfillment of the

Requirements for

Graduation with Honors

by

Ashley E. Warren

Greenville, NC

May 2016

Approved by:

John D. Willson, PhD, PT

Department of Physical Therapy, College of Allied Health Sciences

TABLE OF CONTENTS

ABSTRACT.....	3
BACKGROUND.....	5
PURPOSE OF STUDY.....	7
METHODS.....	8
RESULTS.....	9
DISCUSSION.....	16
CONCLUSION.....	18
REFERENCES.....	19

EFFECT OF ACHILLES TENDON MOMENT ARM ON KNEE JOINT CONTACT FORCE

By: Ashley E. Warren

Approved by: John D. Willson, PhD, PT

Musculoskeletal (MSK) models are used extensively in the study of human movement. The validity of a given MSK model is affected by the architectural features of the system. The Achilles tendon moment arm is one important architectural characteristic of lower extremity MSK models as it transforms ankle plantar flexion moment present during many functional weight-bearing activities to Achilles tendon force. Because the gastrocnemius muscle, which crosses both the knee and ankle joints, inserts to the Achilles tendon, the magnitude of the Achilles tendon moment arm affects knee-joint contact forces. However, current estimates of Achilles tendon moment arm vary widely and are apparently influenced by factors including ankle joint position, measurement technique, and muscle contraction level. For example, some estimates of Achilles tendon moment are a constant value while others vary as a function of ankle angle. Imaging techniques (such as magnetic resonance imaging (MRI)) of the Achilles tendon moment arm tend to be larger than those using ultrasound (US) technology. Finally, estimates of the Achilles tendon moment arm while plantarflexor muscles are contracted tend to be larger than those measured during a state of rest. However, the effect of these varied estimates on knee joint contact and Achilles tendon forces during walking and running is unclear. The purpose of this study is to compare Achilles tendon force and knee-joint contact forces during walking and running using a musculoskeletal model and five different estimates of Achilles tendon moment arm (MRI/contracted, MRI/rest, US/contracted, US/rest, constant value). Three dimensional gait and ground reaction force data from 10 participants will be used as inputs to a knee-joint musculoskeletal model from which tibiofemoral joint, patellofemoral joint, and

Achilles peak force and force*time impulse will be derived using 5 separate Achilles tendon moment arm estimates. Comparisons of the effect of Achilles tendon moment arm will be made descriptively.

Background

The gastrocnemius muscle is a muscle posteriorly located in the lower leg. Along with the soleus muscle, the gastrocnemius works to make up what is more commonly known as the calf. Both of these muscles operate along the entire length of the lower leg, with the gastrocnemius splitting behind the knee; respectively, these bands are referred to as the medial and lateral heads. The gastrocnemius and the soleus both run down the leg as well to connect to the Achilles' tendon, which inserts at the calcaneal tuberosity on the calcaneus. In considering how the gastrocnemius spans both the knee and ankle joints, it follows logic that tension within the gastrocnemius in turn affects the amount of force placed on both of these joints.

Within the context of this study, it is important to note that the aspects of muscle force such as peak force, total force over time (impulse), and rate of force application are essentially the leading cause for all muscle-tendinous and joint-related injuries. This explains why it is imperative to quantify muscle and joint forces precisely; doing so will yield a better understanding of how different joints respond to an increase of imposed force, which will likely lead to improvements in both injury treatment and prevention methods.

Typically, muscle force can be measured in two ways. The first of these is direct and tangible in nature, while the other is made using musculoskeletal models. As could be expected, the direct measurement of muscle force is highly invasive and is therefore rarely performed on human subjects. Because of this, muscle force is more often estimated using musculoskeletal models. Understandably so, the way in which these musculoskeletal models are designed greatly affects the models' results. For example, the distance from the gastrocnemius muscle line of force to the ankle joint will affect the muscle's ability to manufacture torque. For a given muscle

force, shorter moment arms produce less torque, while greater moment arms produce more torque in accordance with the basic formula for joint torque, $T = \text{force} \times \text{moment arm}$.

Several studies find that the Achilles tendon moment arm changes as a function of ankle angle. However, it is not unusual to model the Achilles tendon force using a static moment arm. If the gastrocnemius muscle and Achilles tendon moment arms *do* in fact change as a function of ankle angle, it will be necessary to incorporate these relationships into the approximation of knee and ankle joint forces.

The Achilles tendon moment arm is a highly important architectural feature of lower extremity musculoskeletal models. However, individually determined Achilles tendon moment arm estimates vary across studies depending on what imaging technique, MRI or ultrasound (US), is used, as well as whether the moment arm is measured while the muscles being measured are at rest or contracted. For example, Manal observed larger moment arm estimates using MRI methodology and found that the degree of contraction tends to affect the magnitude of MRI moment arm estimates but not US estimates⁷. Although these discrepancies appear to be consistent, the overall *effect* of these different Achilles tendon moment arm estimates on knee joint forces is currently unclear, which was the sole motivating factor behind this project.

Purpose of Study

This study evaluated effects of differences in Achilles tendon moment arm estimates on tibiofemoral joint, patellofemoral joint, and Achilles tendon force estimates among ten test subjects during walking and running. Due to the fact that some musculoskeletal models fail to take different Achilles tendon moment arm values into consideration, we will be able to evaluate the effect of using various methods of quantifying the Achilles tendon moment arm on the force applied through these tissues as a function of ankle angle during walking and running, relative to a constant value.

Methods

This project was addressed in two phases, which corresponded to the Fall 2015 and Spring 2016 semesters. The first semester included a literature review, which was used for organizational purposes, as well as to generate an equation representing the relationship between the Achilles tendon moment arm and the ankle-joint angle. Each article generated from the literature review was placed into one of four categories based on what method(s) were used to quantify Achilles tendon moment arms: MRI (muscles contracted), MRI (muscles at rest), US (muscles contracted), and US (muscles at rest). The formula generated from the literature review was simply an estimate drawn from the average of all other existing estimates of this relationship, estimates which came from each of the four aforementioned categories.

The second phase focused on comparing knee-joint impact forces with that of Achilles tendon force approximations. This was done using a constant moment arm to the ankle joint, as well as the four equations developed in the first phase of the project. For the context of this study, 3D lower extremity hip, knee, and ankle joint angles and net joint moments during walking and running from ten test subjects were used. After gait data collection took place, each of the ten test subjects' information was entered into a knee joint musculoskeletal model², where it was analyzed with 5 different estimates for the Achilles tendon MA (constant value and four conditional categories) as a function of ankle angle and used to generate the data seen in Figures 2-7 and Tables 1-6.

Average loading rate (LR), force*time impulse, and peak force for the Achilles tendon, patellofemoral (PFJ), and tibiofemoral (TFJ) joint forces were evaluated for each Achilles tendon moment arm estimate. Mean values and percent differences from the reference condition (constant moment arm) were evaluated descriptively.

Results

Five estimates of Achilles tendon moment arm were derived as a function of ankle angle (Figure 1). Visual inspection of this figure suggests that, relative to a constant moment arm, estimates using MRI and the center of rotation method were greater with the ankle plantarflexed, and smaller with the ankle dorsiflexed. However, Achilles tendon moment arm calculated using ultrasound and the tendon excursion method was smaller than the constant value across all ankle positions.

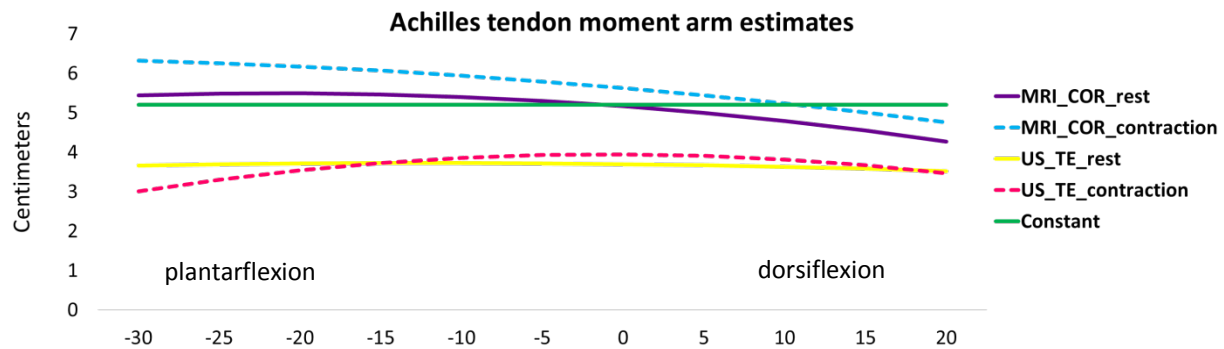


Figure 1. Average Achilles tendon moment arm estimates as a function of ankle angle across previous literature organized by methodology (center of rotation (COR) method and tendon excursion method (TE)) and muscle contraction (rest and contracted).

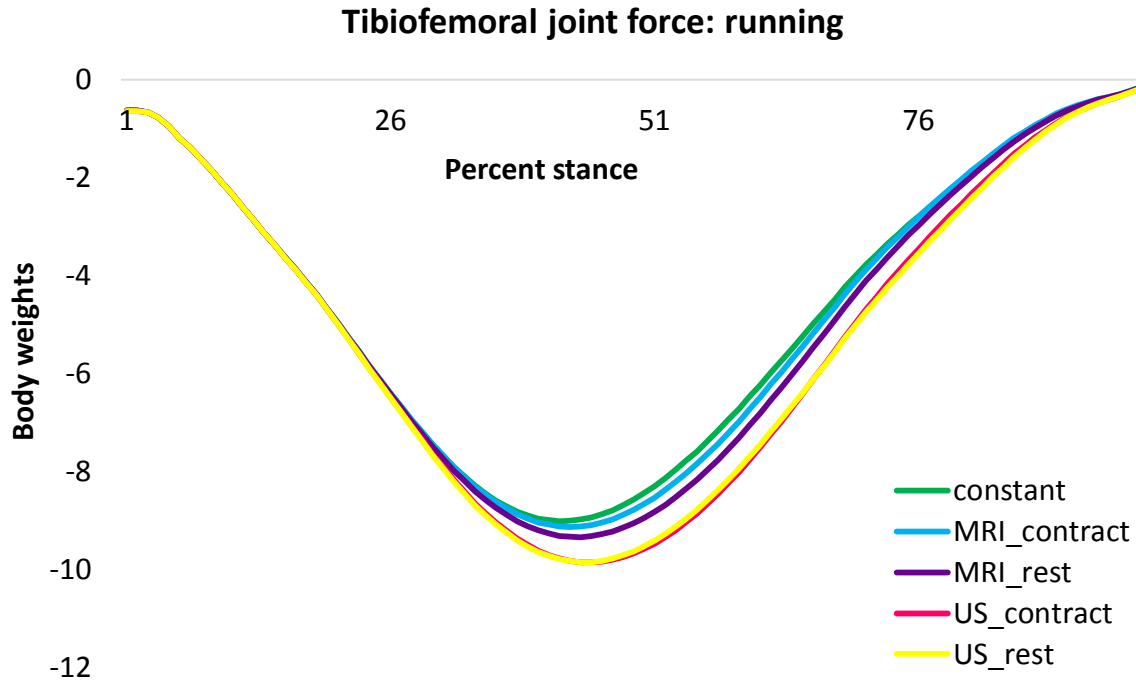


Figure 2. Tibiofemoral joint compression force during running with 5 different estimates of Achilles tendon moment arm at the talocrural joint.

		constant	MRI contract	MRI rest	US contract	US rest
peak force (BW)	Average	-9.06	-9.18	-9.38	-9.90	-9.89
	SD	1.14	1.15	1.16	1.19	1.19
	% diff.	N/A	1.26	3.55	9.20	9.15
impulse (BW*s)	Average	1.24	1.26	1.29	1.37	1.37
	SD	0.15	0.15	0.15	0.16	0.15
	% diff.	N/A	1.34	4.06	10.68	10.89
LR (BW/s)	Average	101.09	100.93	101.54	103.93	104.48
	SD	17.58	17.40	17.34	17.69	17.85
	% diff.	N/A	-0.16	0.45	2.81	3.35

Table 1. Average tibiofemoral joint compression force dependent variables during running using 5 different estimates of Achilles tendon moment arm at the talocrural joint. Comparisons (% diff) were made with a musculoskeletal model with a constant value (5.2 cm).

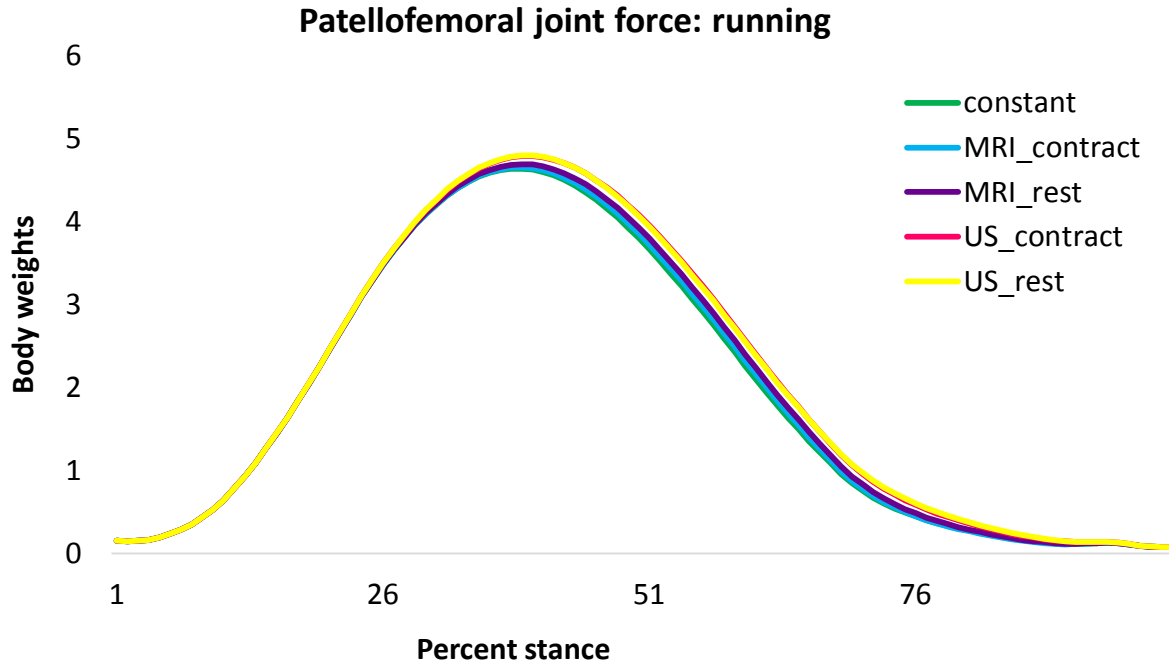


Figure 3. Patellofemoral joint compression force during running with 5 different estimates of Achilles tendon moment arm at the talocrural joint.

		constant	MRI contract	MRI rest	US contract	US rest
peak force (BW)	Average	4.70	4.72	4.75	4.85	4.86
	SD	0.89	0.89	0.89	0.89	0.89
	% diff.	N/A	0.33	1.12	3.15	3.30
impulse (BW*s)	Average	0.52	0.53	0.53	0.55	0.55
	SD	0.12	0.12	0.12	0.12	0.12
	% diff.	N/A	0.77	2.27	5.91	6.00
LR (BW/s)	Average	72.87	72.75	72.85	73.29	73.41
	SD	11.34	11.37	11.34	11.34	11.32
	% diff.	N/A	-0.16	-0.04	0.57	0.74

Table 2. Average patellofemoral joint compression force dependent variables during running using 5 different estimates of Achilles tendon moment arm at the talocrural joint. Comparisons (% diff) were made with a musculoskeletal model with a constant value (5.2 cm).

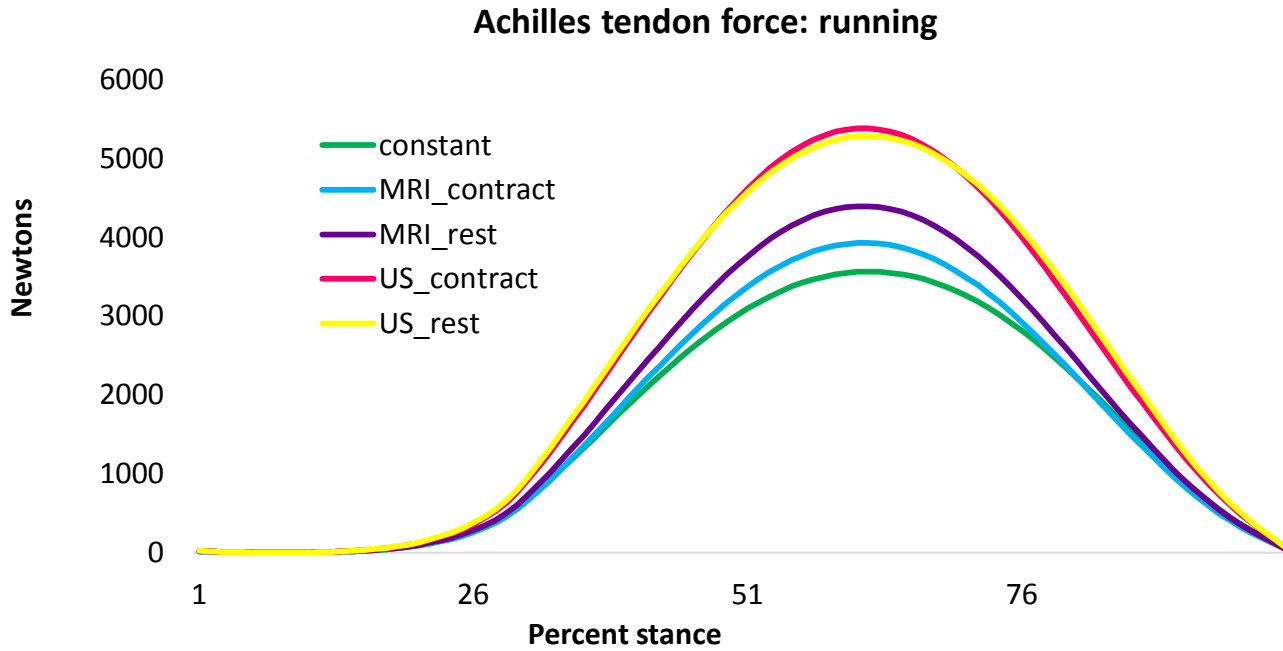


Figure 4. Achilles tendon force during running with 5 different estimates of Achilles tendon moment arm at the talocrural joint.

		constant	MRI contract	MRI rest	US contract	US rest
peak force (N)	Average	3590.79	3958.60	4430.66	5424.45	5326.35
	SD	1224.13	1323.34	1474.88	1800.43	1802.53
	% diff.	N/A	10.24	23.39	51.07	48.33
impulse (N*s)	Average	410.99	434.24	481.57	597.24	601.32
	SD	138.80	144.94	160.32	198.58	202.13
	% diff.	N/A	5.66	17.17	45.32	46.31
LR (N/s)	Average	49014.84	54222.07	60681.25	74051.68	72732.28
	SD	16917.77	18009.84	19927.48	24202.29	24710.11
	% diff.	N/A	10.62	23.80	51.08	48.39

Table 3. Average Achilles tendon force dependent variables during running using 5 different estimates of Achilles tendon moment arm at the talocrural joint. Comparisons (% diff) were made with a musculoskeletal model with a constant value (5.2 cm).

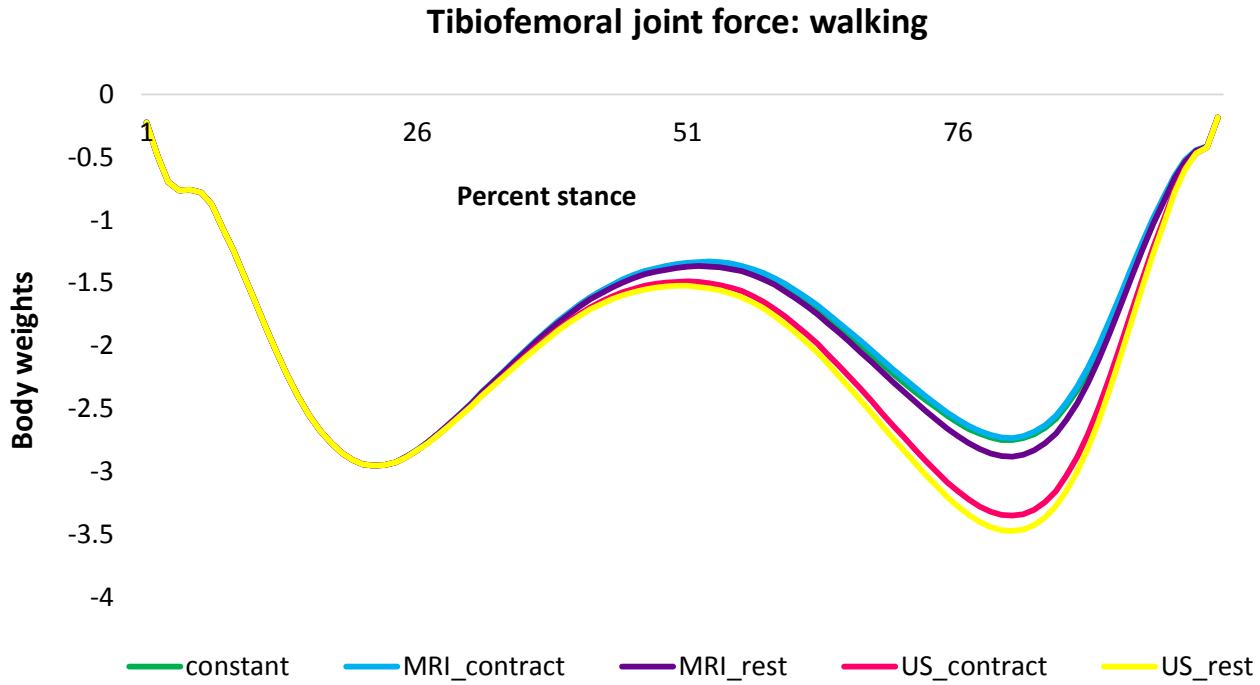


Figure 5. Tibiofemoral joint compression force during walking with 5 different estimates of Achilles tendon moment arm at the talocrural joint.

		constant	MRI contract	MRI rest	US contract	US rest
peak force (BW)	Average	-3.11	-3.10	-3.15	-3.43	-3.53
	SD	0.33	0.33	0.29	0.27	0.28
	% diff.	N/A	-0.27	1.24	10.36	13.51
impulse (BW*s)	Average	1.27	1.26	1.29	1.39	1.42
	SD	0.09	0.09	0.09	0.10	0.10
	% diff.	N/A	-0.89	1.55	9.80	12.10
LR (BW/s)	Average	23.04	23.04	23.04	23.04	23.05
	SD	6.91	6.92	6.91	6.91	6.91
	% diff.	N/A	0.00	0.00	-0.01	0.01

Table 4. Average tibiofemoral joint compression force dependent variables during walking using 5 different estimates of Achilles tendon moment arm at the talocrural joint. Comparisons (% diff) were made with a musculoskeletal model with a constant value (5.2 cm).

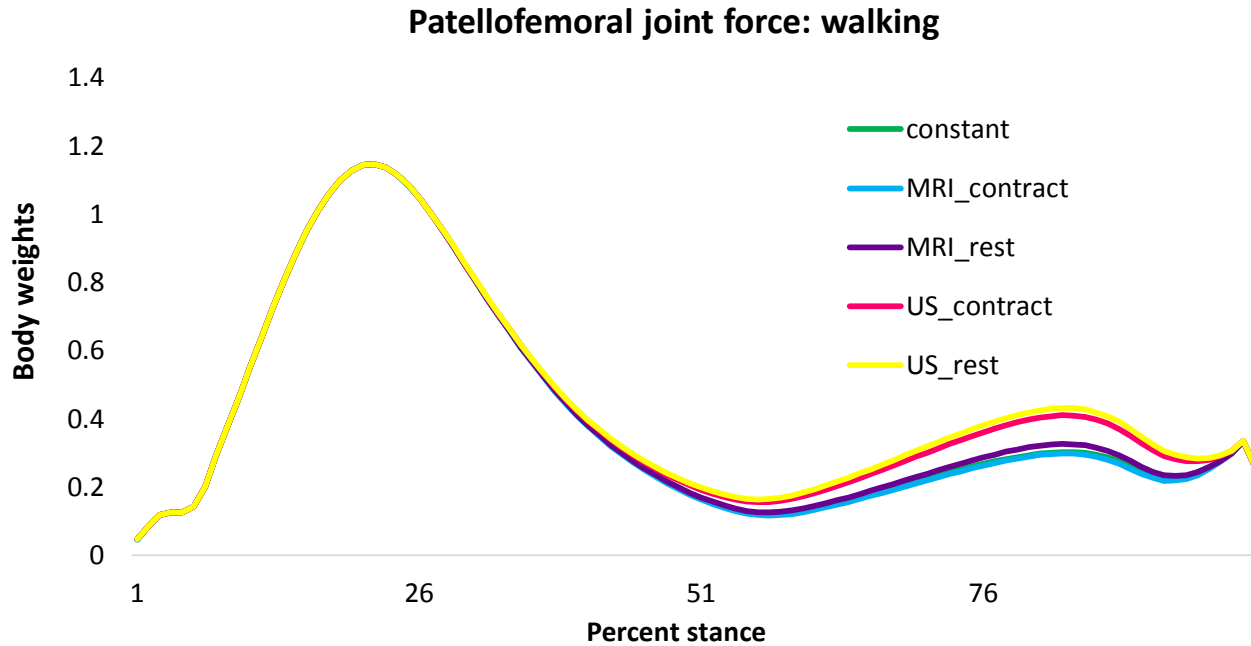


Figure 6. Patellofemoral joint compression force during walking with 5 different estimates of Achilles tendon moment arm at the talocrural joint.

		constant	MRI contract	MRI rest	US contract	US rest
peak force (BW)	Average	1.18	1.18	1.18	1.18	1.18
	SD	0.27	0.27	0.27	0.27	0.27
	% diff.	N/A	-0.01	0.00	0.02	0.03
impulse (BW*s_)	Average	0.28	0.27	0.28	0.30	0.30
	SD	0.04	0.04	0.04	0.04	0.04
	% diff.	N/A	-0.78	1.32	8.18	10.08
LR (BW/s)	Average	13.05	13.05	13.05	13.05	13.05
	SD	3.40	3.40	3.40	3.40	3.40
	% diff.	N/A	0.00	0.00	0.00	0.00

Table 5. Average patellofemoral joint compression force dependent variables during walking using 5 different estimates of Achilles tendon moment arm at the talocrural joint. Comparisons (% diff) were made with a musculoskeletal model with a constant value (5.2 cm).

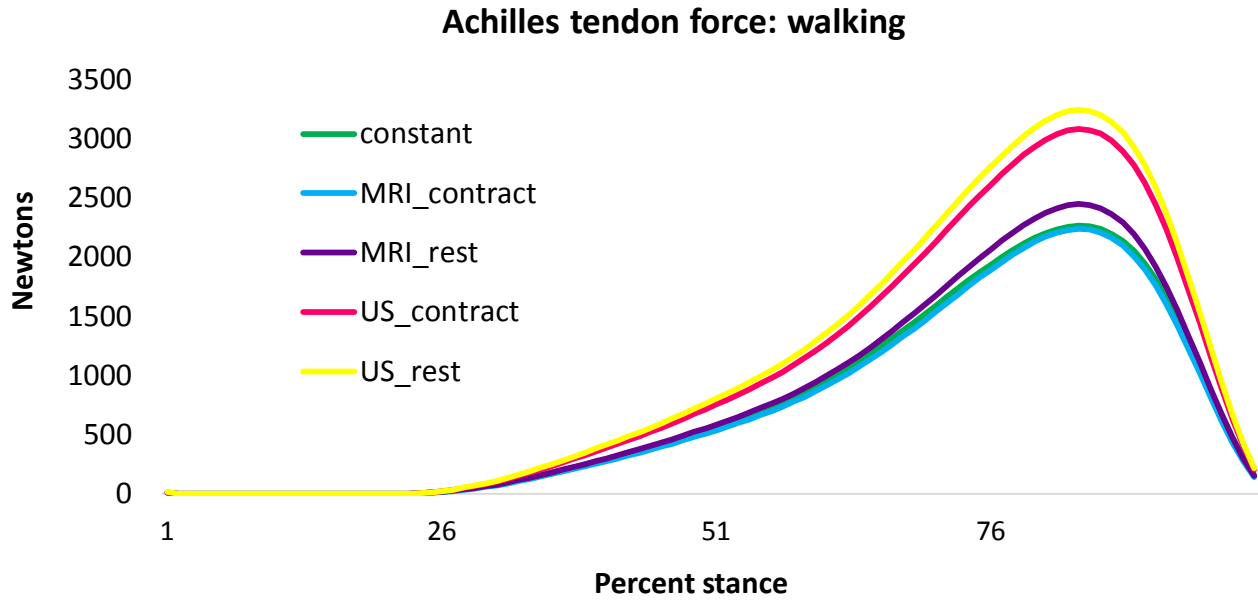


Figure 7. Achilles tendon force during walking with 5 different estimates of Achilles tendon moment arm at the talocrural joint.

		constant	MRI contract	MRI rest	US contract	US rest
peak force (N)	Average	2296.23	2268.77	2480.48	3124.30	3288.88
	SD	644.61	634.74	694.83	877.11	921.76
	% diff.	N/A	-1.20	8.02	36.06	43.23
impulse (N*s)	Average	505.86	488.91	533.59	679.75	720.19
	SD	201.66	190.61	207.80	268.03	285.36
	% diff.	N/A	-3.35	5.48	34.37	42.37
LR (N/s)	Average	5715.96	5392.10	5873.14	7577.65	8085.63
	SD	1984.59	1847.21	2010.28	2617.76	2800.21
	% diff.	N/A	-5.67	2.75	32.57	41.46

Table 6. Average Achilles tendon force dependent variables during walking using 5 different estimates of Achilles tendon moment arm at the talocrural joint. Comparisons (% diff) were made with a musculoskeletal model with a constant value (5.2 cm).

Discussion

The results showed that MRI Achilles tendon moment arm estimates were 29-77% greater across ankle positions, in comparison to ultrasound estimates. This resulted in decreased peak force estimates, specifically in the Achilles joint force. As can be seen in Figures 4 and 7, as well as Tables 3 and 6, the Achilles joint force was 35% greater when subjects were walking and 28% greater during running. The other two knee joint contact forces of interest, the tibiofemoral joint (TFJ) (Figures 2 and 5; Tables 1 and 4) and the patellofemoral joint (PFJ) (Figures 3 and 6; Tables 2 and 5), were subjected to smaller differences between estimate conditions. The tibiofemoral joint was 11% greater when subjects were walking, while running estimates were approximately 7% larger. Lastly, the patellofemoral joint forces were 2% greater in running estimates and even less than 1% greater in walking estimates.

On average, Achilles tendon moment arm estimates were 6% larger with the plantarflexors contracted, which again reduced the peak force estimates. As was the case when determining percent differences between conditional estimates, the Achilles joint force saw the largest difference, specifically 7% during walking and 4% during running. The tibiofemoral joint also saw significantly lower percent differences; these values were 2% during walking and 1% while running, respectively. The patellofemoral joint was subjected to less than a 1% difference during both walking and running.

As might be expected, the knee joint contact forces evaluated for the scope of this project were each sensitive to the magnitude of the Achilles tendon moment arm. However, effects are most notable at the Achilles joint force and more notable at the tibiofemoral joint than the patellofemoral joint, which was hardly affected at all. In comparison to the reference, or

constant, value, greater knee joint forces are produced with either MRI or ultrasound procedure as a function of increasing ankle plantarflexion.

Conclusion

Although percent differences between experimental conditions vary considerably, the magnitude of the Achilles tendon moment arm affects peak TFJ, PFJ, and Achilles tendon force, impulse, and average loading rates. In additional consideration with the obtained results, comparison of these loading conditions across other studies with different methodologies should be made.

The ankle plantarflexors are active during stance phase, or the interval of gait phase that extends from heel strike to toe push-off, of many common functional activities. Achilles tendon moment arm estimates made with the plantarflexors contracted are likely the best form of measurement.

It is worth noting that while we lack a “gold standard” to which we can compare, and therefore judge the validity of estimates, for this project we chose only to report the range of values at each site that one could expect across studies using moment arms derived using various methodologies. This is still meaningful, though, so that we do not misread research findings as “different” when they actually are not.

References

1. Clarke E.C., et al. A non-invasive, 3D, dynamic MRI method for measuring muscle moment arms in vivo: demonstration in the human ankle joint and Achilles tendon. *Med Eng Phys*. 2015 Jan;37(1):93-9. doi: 10.1016/j.medengphy.2014.11.003.
2. DeVita P., and Hortobagyi T. Functional knee brace alters predicted knee muscle and joint forces in people with ACL reconstruction during walking. *J Appl Biomech* (2001). 17, 297-311.
3. Fath F., et al. Direct comparison of in vivo Achilles tendon moment arms obtained from ultrasound and MR scans. *J Appl Physiol* (1985). 2010 Dec;109(6):1644-52. doi: 10.1152/japplphysiol.00656.2010.
4. Kawakami Y., et al. In vivo estimation of human Achilles tendon moment arm based on ultrasonography. *American Society of Biomechanics* (2001).
5. Klein P., Mattys S., and Rooze, M. Moment arm length variations of selected muscles acting on talocrural and subtalar joints during movement: and *in vitro* study. *J Biomechanics* (1996). 29(1). 21-31.
6. Maganaris C., Baltzopoulos V., and Sargeant A. In vivo measurement-based estimations of the human Achilles tendon moment arm. *Eur J Appl Physiol* (2000). 83, 363-369.
7. Manal K., Cowder J.D., Buchanan T.S. Subject-specific measures of Achilles tendon moment arm using ultrasound and video-based motion capture. *Physiol Rep*. 2013 Nov;1(6):e00139. doi: 10.1002/phy2.139.

8. Rugg S.G., et al. *In vivo* moment arm calculations at the ankle using magnetic resonance imaging (MRI). *J Biomechanics* (1990). 23(5). 495-501.